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A Loblolly Pine
Management Guide

Foresters' Primer in Nutrient Cycling

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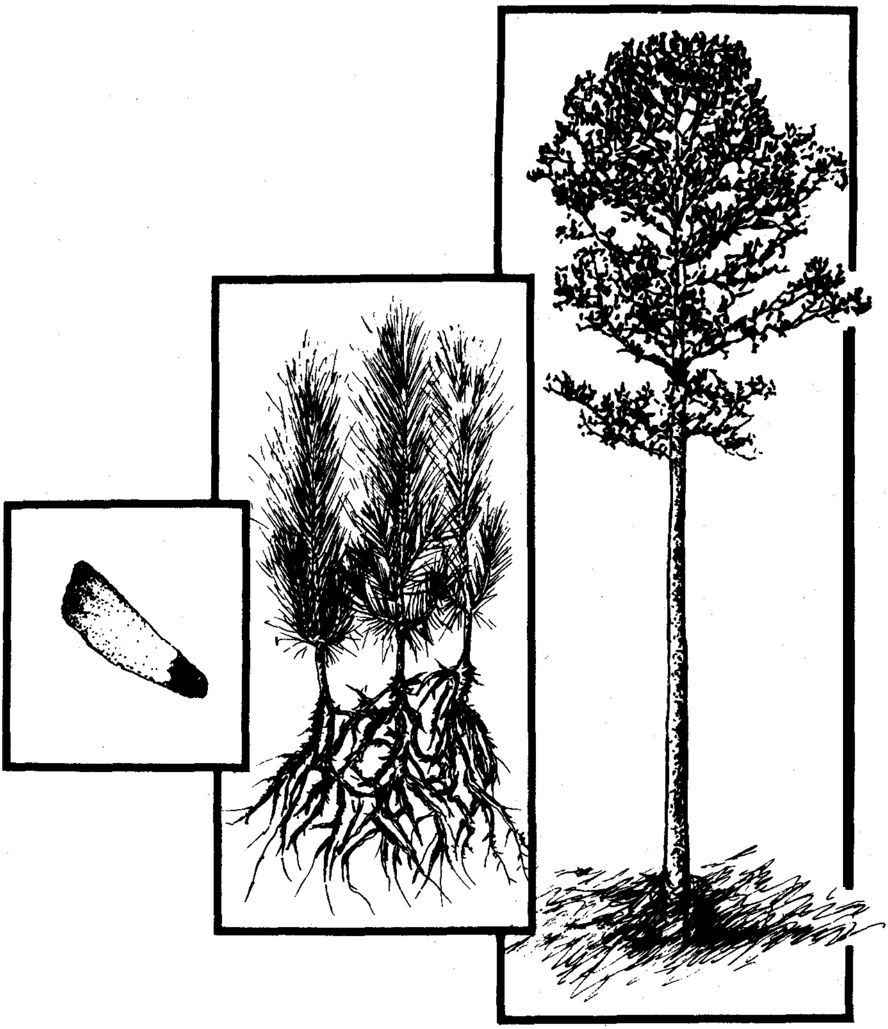

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ABSTRACT

The nutrient cycle, which includes the inpu of nutrients to the site, their losses, and their m ve-ment from one soil or vegetation component to an ther, can be modified by site preparation, rotation le gth, harvest system, fertilization, and fire, and by sing soil. We report how alternative procedures affe t site nutrients, and we provide general principle that can he followed to enhance long-term productivit of loblolly pine.

Keywords: _Pinus taeda_, nitrogen, phosphorus, po as-sium, rotation length, nitrogen fixing, whole-tr e harvesting.

One key to sustained yield in forest y is the maintenance or improvement of soil fertil ty through good soil management. Such manag ment requires understanding of nutrient cyclin , which is the circulation of nutrients in the fo est eco-system. In each ecosystem, circulation o nutri-ents follows specific pathways. Cycling atterns can only be described in broad terms beca se rates and directions of movement vary with stan con-ditions. Some general processes regulati g nutri-ent flow within a forest system can be id ntified, however: (1) uptake by higher plants, (2 trans-location and use within the plants, (3) r turn to the soil and forest floor, (4) mineraliza ion, immobilization, and leaching of the retur ed nutri-ents, (5) inputs of nutrients from atmosp eric, geologic, and biological sources, and (6) losses in streamflow, harvesting, and volatiliza ion to the atmosphere.

Concerns about potential declines in forest productivity through loss of soil nutrien s are not new. Over a century ago, experiments deter-mined that excessive removal of nutrient-containing litter by Bavarian peasants wa detrimental to tree growth. When this ad erse effect was clearly established, litter ga hering was discontinued.

Despite that experience, the prevail·ng view of silviculturists until recently was thal mineral elements would "take care of themselves" ‹r that the loss of nutrient elements through the exploitation of timber was not very serious if 'eaves and twigs were left behind. In 1955, an ınalysis of the requirements for forest growth on ‹ poor site in England showed demands for nutrieıts exceeded the supply. Few noticed that th·s forest soil was similar to many forest soils in ·he Southeastern United States. Only recently hav‹ southern foresters recognized that conservatioı and replenishment of nutrients are as importaıt in forest management as is determination of otation length or thinning schedule.

Pines are adapted to infertile soils in part because they require smaller amounts of nıtrients than do other plants. Recent work, howev‹r, has revealed some additional possible mechani:ms: (1) conservation of available nutrients by miıimizing losses to deeper soil layers or to the atr osphere (tight nutrient cycles), (2) minimizing l‹sses from the cycle by temporarily immobilizin‹ nutrients, primarily in the soil organic layer!, (3) collection and retention of nutrients fror inputs to the cycle (from the atmosphere and wea'hering), (4) reuse of nutrients within the tree, aıd (5) evolution of special mechanisms, such as ıycorrhizae, that obtain nutrients from sources n‹t readily available. Regardless of the mechani:ms used, the pine ecosystem, like those of other p'ants, is sensitive to disturbances that might redu‹e its ability to obtain, retain, or cycle nutri‹nts. Disturbances such as harvesting, fertiliz‹tion, burning, and changes in atmospheric input! all affect cycling. Understanding of these p ocesses and their interrelationships, therefore, s necessary for maintenance of forest productivi·y.

Ecosystem Components

The forest ecosystem can be divided nto three major components--mineral soil, for‹st floor, and vegetation. Each major component can be further divided into smaller components or pools (fig. 1). With data for each pool and information on the influence of management practices, flow models can be developed that show the rate of nutrient transfer from one pool to another. Predictions of nutrient availability, and thus production, can be made based upon changes in the pool quantities and on the transfer rates between pools.

A number of factors complicate such predictions at any given time, however. For example, relatively small additions by biological nitrogen

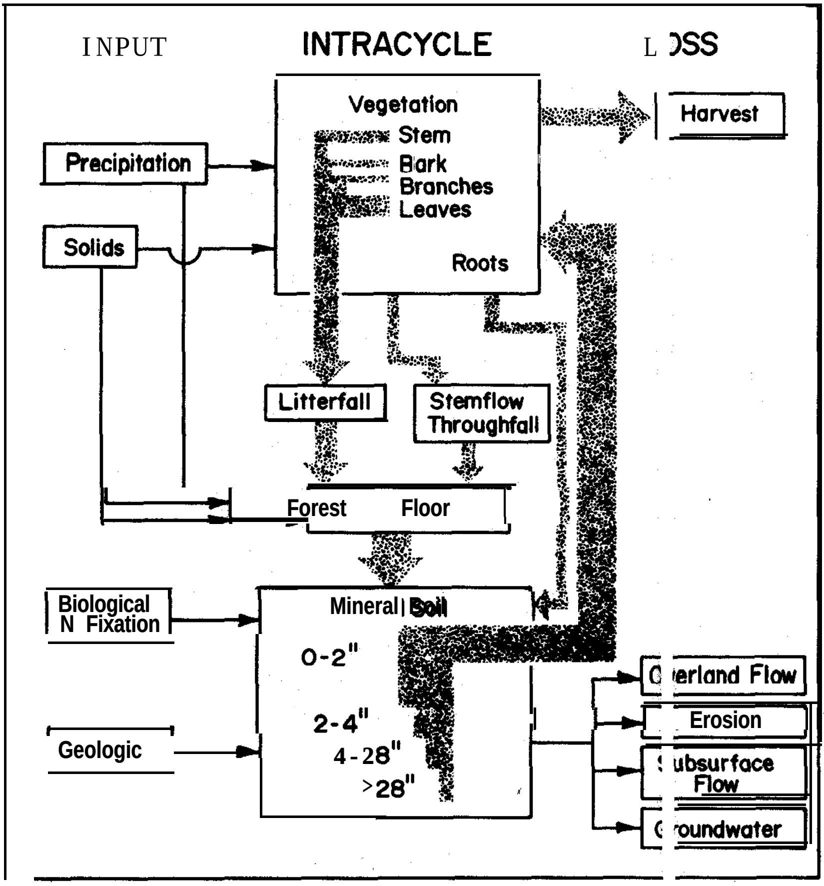

Figure 1.--The nutrient cycle in a loblolly pine stand.

(N) fixation, or nutrient losses by leach ng, may influence growth for several rotations of trees. Therefore, extrapolation of the effects o extensive treatments, such as fertilization, o'er long time periods should be done cautiously an with some knowledge of the potential for error

Quantitative nutrient cycling data a e needed, however, to address some major fo estry problems with harvesting systems, fertili ation, and environmental protection. Currently, research in fertilization is primarily directed to ard increased yield and toward delineation of sites where trees will respond to fertilization In the long term, forest fertilization practices based upon a knowledge of nutrient cycling will sustain or improve yields.

Each nutrient or element has its own peculiar system of cycling, but the systems h ive similarities. N is largely in organic compou ids and requires biological action for its releas. Phosphorus (P) is in both organic and inorgan c materials and its availability is strongly in luenced by chemical reactions. Potassium (K) is almost totally inorganic , and is in equilibrium between the native, fixed, and exchangeable forms, Due to these. and other variations, there is no single cycle: Rather, there are many cycles, on for each element under each separate conditic.

From this general introduction, it i; evident that cycling can he altered by modificati ns of the forest environment. We shall examine the components of the cycles and the influences of management practices thereon. Because it has been shown that loblolly pine (*Pinus taeda* L.) respc nds most readily to N and P fertilization, emphasis will be placed on these two elements.

Nutrient Inputs to the Forest

In nature, nutrients are added to a loblolly pine system from: (1) the atmosphere as dry gases and particulates or as materials dissolved in wet precipitation, (2) weathering of soil mirerals, and (3) biological fixation of N.

Atmospheric Inputs

Precipitation contributes significant amounts of nutrients for growth and maintenance of loblolly pine. Average annual inputs per acre (ha) throughout the tree's range are 5.4 lb (I kg) of N, 0.4 lb (0.4 kg) of P, 1.5 lb (1.7 kg) of K, 6.4 lb (7.2 kg) of calcium (Ca), and 1.5 lb (1.7 kg) of magnesium (Mg). Variation between areas may be great; areas of high precipitation tend to have more nutrient inputs than those with low precipitation. Other factors may influence the chemical composition of precipitation. Areas near the ocean can receive marine aerosols that are high in sodium, magnesium, chloride, and sulphate. Sites near urban and industrial areas can receive increased quantities of sulphate sulfur and nitrate and ammonium N. Around smelters, quantities of sulfur and minor elements may be sufficient to adversely affect plant growth. At worst, all but the most resistant vegetation may be destroyed.

Gaseous and particulate inputs in the absence of precipitation are usually referred to as dry deposition. Unfortunately, there are few quantitative measurements of dry deposition. Mechanisms related to dry deposition include filtering of atmospheric particles by tree canopies, absorption of water-soluble gases onto moist surfaces, and the direct gaseous uptake via leaf stomata. Sulfur dioxide and gaseous ammonia may also be directly absorbed by the soil.

Weathering Inputs

Weathering refers to nutrient release from primary and secondary soil minerals by geochemical and biogeochemical processes. In the South, release of nutrients depends on soil parent material and may vary greatly between sites. In general, the older and more deeply weathered the soil, the less will be the potential for nutrient release. On highly weathered soils, atmospheric deposition, rather than weathering, is the major source of natural replenishment for the small leaching losses that may occur.

Biological N Fixation

Biological fixation can be an important source of N. N is fixed by legumes, nodulated nonlegumes, and, in some instances, by lichens that include blue-green algae. Except under unusual circumstances, free-living organisms--bacteria and algae--contribute only insignificant amounts of N. In loblolly pine stands with closed canopies, N fixation from all sources probably does not exceed a few pounds per acre annually. The major sources of this fixation are nodulated nonlegumes such as southern bayberry (*Myrica cerifera* L.) and many species of legumes. The latter are especially important for brief periods after fires. Fixation by free-living bacteria and algae is limited by energy sources, low soil pH, and nutrients; it usually contributes less than 1 pound per acre of N annually. Mycorrhizae have not been shown to fix N. The apparent fixation sometimes associated with mycorrhizae is accomplished by free-living organisms in the soil areas influenced by the roots and their mycorrhizal associates.

Nutrient Pools and Cycling

Nutrient pools change rapidly after ecosystem disturbances such as wildfire, harvesting, and site preparation but again reach an equilibrium as stands mature (figs. 2, 3, 4).

Understory Vegetation

The nutrient content of herbaceous biomass peaks soon after plantation establishment. This

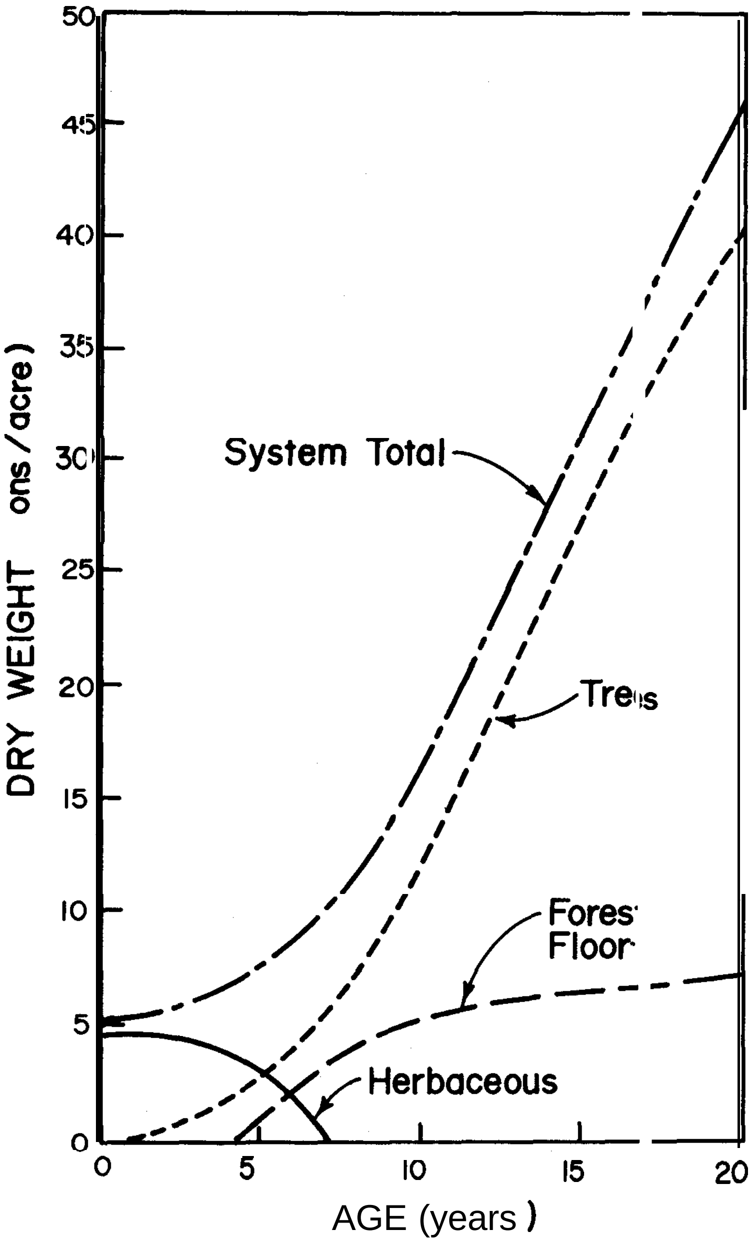

Figure 2.--Biomass accumulation in an unthinned lob olly pine plantation during the first 20 years. (Adapted fro Switzer and Nelson 1972.)

vegetation, an important sink for nutrien s, is usually eliminated after stand closure, 5 to 8 years after establishment. Along with th residues from harvesting, it later provides i portant quantities of nutrients to the developing loblolly pine stand. In one plantation, abovegrourd herbaceous vegetation contained 67 lb (75 kg) of N, 7 lb (8 kg) of P, 9 lb (10 kg) of K, 21 l (23 kg) of Ca, and 7 lb (8 kg) of Mg per acre (ha).

Overstory Vegetation

Rapidly growing young pines quickly accumulate nutrients and develop a forest floor at the expense of the mineral soil and the herbaceous components of the stand. Accumulation of nutrients in the stand proceeds at a fast pace during the first 20 years, slows through age 40, and reaches an equilibrium thereafter (fig.). Maximum nutrient accumulation in foliage of loblolly stands occurs sometime after stand closure, at about 15 years of age, but before there s extensive suppression mortality. As trees are suppressed, foliar nutrient accumulation declines. In the stand as a whole, stem and branch nutrients accumulate relatively uniformly through ge 40, at which time a new equilibrium is reached. A different pattern of nutrient accumulation ccurs in individual surviving trees (fig. 4). Fo the survivors, foliage continues to accumulate utrients at a uniform rate throughout the rotatio . Stems and branches of these trees gradually in rease their rates of nutrient accumulation in contrast to an equilibrium for the stand as a who e.

A vigorously growing loblolly pine plantation can tie up a large portion of the site's nutrients (table 1). Of 2,124 lb of N/acre (2,400 kg/ha) on a site, 286 lb (321 kg) or 13 percent we e in 16-year-old trees. An equal amount of N was in the forest floor. Thus, 26 percent of the site N was immobilized 16 years after planting loblolly pine. The relatively large proportion c site N

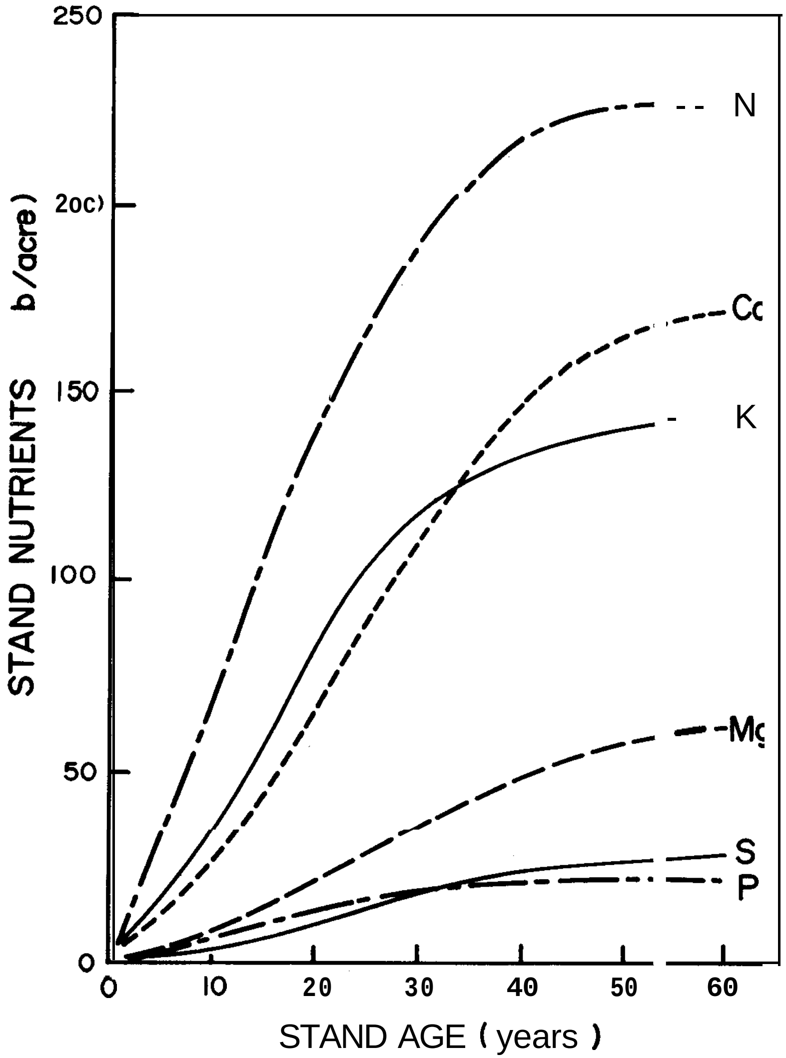

Figure 3. --Accumulation of macronutrients in whole tree; in loblolly pine stands on good sites. (Adapted from Switzer and others 1968.)

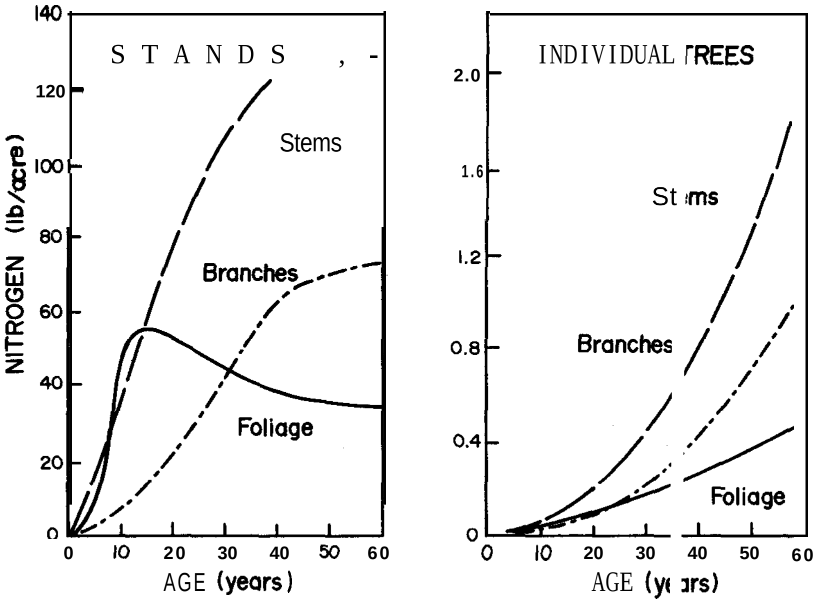

Figure 4.--Accumulation of N in fractions of loblolly pine stands and trees on good sites. (Adapted from Switzer and others 1968.)

in the mineral soil and its low availability explains why N fertilization can often increase growth even though there is an abundance of N on the site. The proportions of P, K, and other elements that are extractable vary widely with site, and reliable measures of their nutritional availability have not been developed.

Needles have relatively little of a tree's biomass, but they have the highest concentrations of nutrients. Among tree parts, stemwood has the lowest concentrations of nutrients. Nutrient concentrations in root biomass could be more accurately described if roots were separated into two categories: permanent woody roots for anchoring the tree and providing channels for conduction, and nonwoody ephemeral roots for collecting nutrients and moisture required for growth. The latter contain relatively high nutrient concentrations compared with the former.

Table 1.--Distribution of tree biomass and nutrients in a 16-year-old loblolly pine plantation in the North Carolina Piedmont

Component	Biomass	N	P[a]	K[a]
	Tons/acre	--- Pounds/acre	(%)	---
Trees				
Needles	3.6	73	9	43
Branches	10.3	54	5	25
Stemwood	6.8	70	10	58
Stembark	16.2	32	4	21
Roots		57	15	54
Total tree	85.8	286 (13)	43 (1)	201 (34)
Forest floor	--	274 (13)	27 (7	25 (4)
Mineral soil, 0-28 in.	--	1,564 (74)	331 (8;)	360 (62)
Site total	--	2,124	401	586

[a]Values represent total quantities in vegetation and Forest floor and extractable amounts in mineral soil.

Forest Floor

Nutrients and organic matter accumulate in the forest floor as a loblolly pine stand develops. Litter accumulates most rapidly between the time the stand closes and the time when stand foliage is at a maximum, about 15 years of age. In one plantation, the accumulation rate was nearly 2 tons/acre/year (4 t/ha) between ages 13 and 16. Accumulated litter reaches an equilibrium of 13 to 16 tons/acre (30 to 35 t/ha) somewhere between stand age 16 and 30 (fig. 5).

Nutrient contents of forest floors in loblolly pine stands vary greatly, probably because of differences in climate and soil. The forest floor of a 15-year-old plantation in Mississippi contained only about one-third as much N and P, half as much K, and two-thirds as much Ca and Mg as did that of a 16-year-old North Carolina plantation. In the forest floors of five 15-rear-old

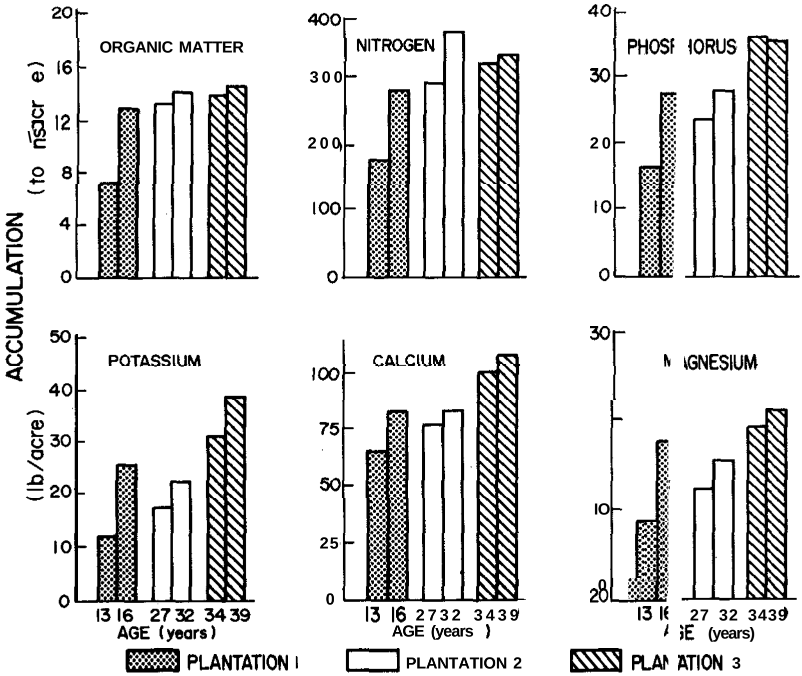

Figure 5.--Accumulations of organic matter, N, P, K, Ca, and Mg in the forest floor of three plantations at various ages.

plantations in Virginia, there was slightly less N, P, K, and Mg, but more Ca than in the North Carolina plantation. Although the forest Floors of the three Piedmont North Carolina plantations shown in figure 5 had approximately reached a biomass equilibrium at age 16, nutrient contents continued to change. Differences between plantations were probably caused by the influences of stand density and soil on initial needle composition and rate of decomposition.

Decomposition and nutrient release rites of forest floor materials are highest in the first year after litterfall, but each element or component changes at its own rate. During tle first year, about 25 percent of the organic material, 50 percent of the P, 70 percent of the K, 25 percent of the Ca, and 57 percent of the Mg, but only 10

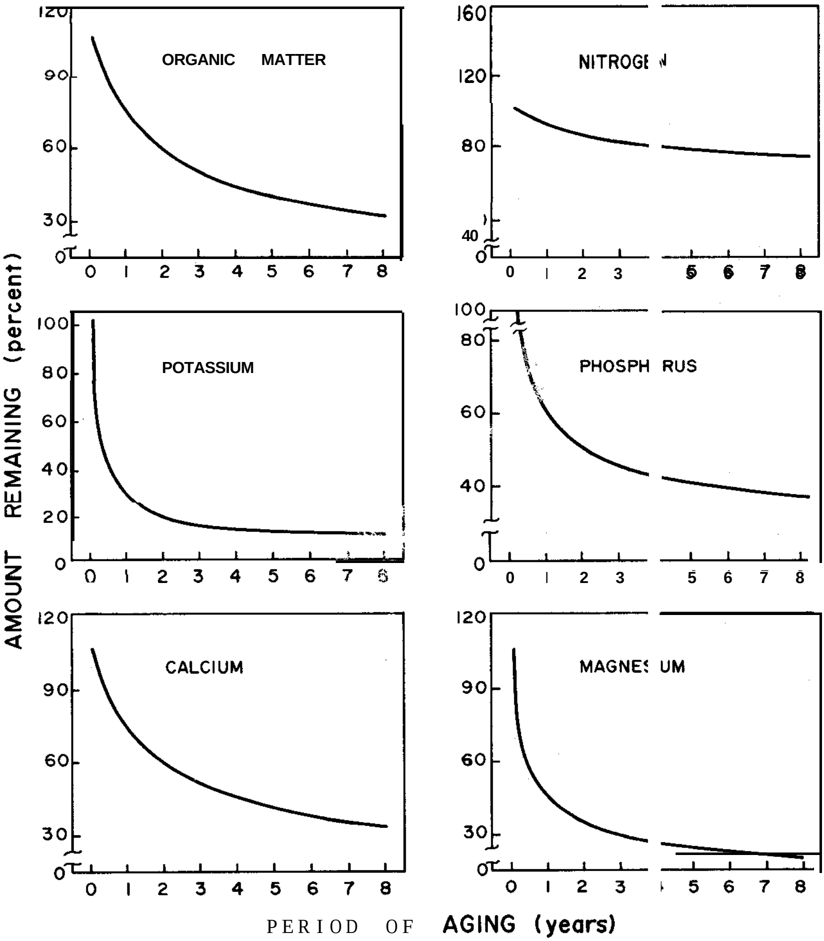

Figure 6. --Percentages of initial organic matter, N, P K, Ca, and Mg remaining in the forest floor after 8 years of decompo ition.

percent of the N, are lost. After 8 yea s of decomposition , about two-thirds of the o ganic material, 60 percent of the P, 90 percen of the K, 67 percent of the Ca, and 79 percent f the original quantity of Mg are lost. Net d crease of N during this period is only 27 percent fig. 6).

Forest floors of closed, growing lo lolly pine plantations, regardless of age, may be similar in weight, nutrient content, and, ex ept for

N, nutrient release (tables 2, 3). Differences may occur, however, in the distribution of nutrients within the forest floor layers and in the proportions of nutrients released from the layers. In a lg-year-old plantation, the majority of biomass and nutrients were in forest floor malerials less than 8 years old (table 2). In a 40-year-old stand, forest floor materials younger and ilder than 8 years each held about half of the nutrients. Except for N, however, the majority of nutrients are released from forest floor layers less than 8 years old, regardless of stand age (table 3). Older forest floor layers in a young stand accumulate rather than release elemerts. In the 40-year-old stand, nutrients in the forest floor layers older than 8 years of age are released, but more slowly than from younger material. Thus, it appears that until forest floor biomass is in equilibrium with litterfall, older layers do not contribute important amounts of nutrients for tree growth. Before about age 20, the older layers act as nutrient sinks or reserves for cycling at a later time.

Many factors control the accumulation rate and the point at which forest floor biomass decomposition and nutrient release come into equilibrium with litterfall. These equilibria differ

Table 2.--Components of the forest floor of two loblolly pine plantations

Component	Forest floor layer age (years					
	1 through 8		Over 8		All ages	
	Plantation age (years)					
	19	40	19	40	19	40
	Pounds/acre					
Organic matter	22,276	18,259	3,623	11,055	25,8[illegible]	29,314
Nitrogen	283	212	71	159	3[illegible]	371
Phosphorus	23.7	15.6	9.2	**16.9**	32.[illegible]	32.5
Potassium	14.3	12.3	3.8	13.5	18.[illegible]	25.8
Calcium	94.2	62.1	21.6	43.2	115.[illegible]	105.3
Magnesium	12.8	8.9	4.0	9.6	16.[illegible]	**18.5**

Table 3.--Annual release (accumulation) of nutrients from the forest floors of two loblolly pine plantations

Nutrient	Forest floor layer age (years)					
	1 to 8		Over 8		All ages	
	Plantation age (years)					
	19	40	19	40	19	To--
	------ Pounds/acre ------					
Nitrogen	13.1	9.1	2.5	16.6	15.6	25.7
Phosphorus	4.8	3.3	(0.4)	1.8	4.4	5.1
Potassium	11.2	10.1	(0.2)	1.2	11.0	11.3
Calcium	15.6	11.8	0.4	3.7	16.0	15.5
Magnesium	4.4	3.4	0.2	0.7	4.5	4.6

among nutrients. Understanding the agents controlling decomposition and nutrient release will lead to improved tree growth and a reduction in the need for fertilization under intensive forest management.

Mineral Soil

Mineral soil contains a majority of the ecosystem's nutrient reserves. In one Piedmont plantation., about three-quarters of all the site's N was in the mineral soil to a depth of 28 inches (70 cm) (table 1). Comparisons of the proportions of P, K, Ca, and Mg in biomass plus forest floor and in the mineral soil are meaningless because the bases for element measurements differ. In the forest floor, total nutrients are measured; in the soil, only extractable forms are measured. Nutrient analyses of mineral soils have been adapted from agriculture. While appropriate for annual agronomic crops, these tests are often inadequate as indices of long-term nutrient supply in forest ecosystems. The tests are not capable of estimating the size of the mineral soil nutrient reservoir. They indicate only the soil's ability to release nutrients under a particular set of conditions. Even where total nutrient are measured, as with N, availability can only be roughly gauged. Nitrogen mineralization and availability are the result of numerous uncontrolled, unforeseen, and unknown factors that affect the presence and activity of the microorganisms responsible for N transformation, Thus, soil tests provide only rough approximations of potential total nutrient supply.

During the first few years after loblolly pine is established on sites without a forest floor, most of the nutrients required for tree growth and accumulation of the forest floor are supplied by the mineral soil. In a loblolly pine plantation established on an old field in the South Carolina Piedmont, N decreased markedly throughout the surface 24 inches (60 cm) of mineral soil during the first 15 years (fig. 7). During the next 5 years, there was little decline, Declines over the first 15 years were also observed for extractable K, Ca, and Mg. Extractable P decreases were noted only to a depth of 3 inches

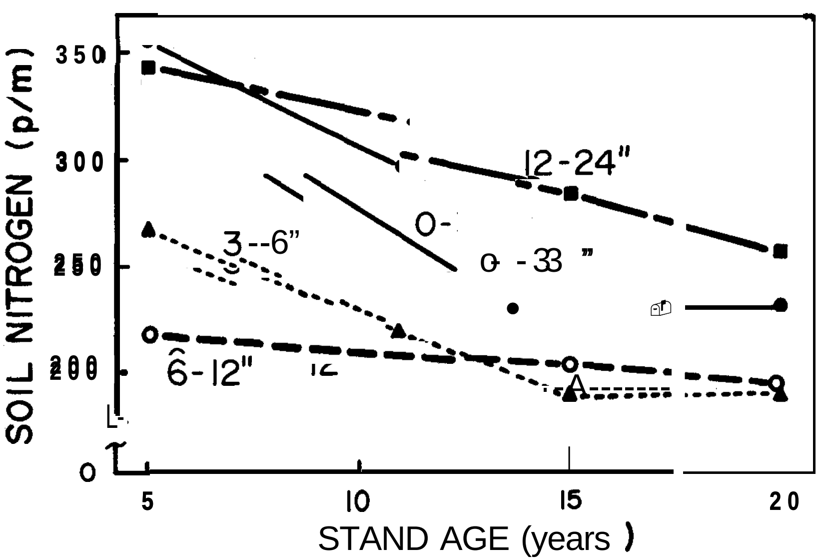

Figure 7.--Changes in N content of mineral soil in an old-field loblolly pine plantation over a 20-year period.

(8 cm), possibly because below this depth the extractable P concentrations were extremely low. Nutrient changes in the mineral soil of loblolly pine stands between 20 and 40 years of age appear to be small. During this time, the forest floor can provide the majority of nutrients required for growth. Lack of further nutrient drawdown in the mineral soil may also be due to the depletion of readily available reserves.

Little information is available on the recharge of mineral soil depleted of nutrients during the first stages of a stand's growth. If recharge occurs, it would be after about 40 years of age (figs. 4, 5). At this time, uptake of nutrients by vegetation may be more than balanced by a loss in dying vegetation. The excess nutrients released by the decomposing roots and forest floor could aid in the preparation of the mineral soil to become a nutrient source when a succeeding stand develops.

Declines of nutrients in the mineral soil of old fields after pine planting illustrate the importance of the soil's nutrient supply during plantation establishment. What is not answered, however, is whether this old-field situalion is representative of what occurs when natural stands or plantations with a forest floor are regenerated. Treatments that diminish the forest floor as a source of nutrients may prolong the stand's reliance on the mineral soil. On infertile or intensively harvested sites, declines related to nutrient deficiencies may take place unless fertilizer is applied.

The Loblolly Pine Nutrient Cycle

Within the stand, nutrients move belween and within the three major components: the living vegetation, the forest floor, and the mireral soil. Some factors that determine from which source nutrients are obtained include age and stage of stand development, and amount and availatility of nutrients in the component or subcomponert.

Nutrients are transferred from one component to another by trees through litterfall, crown leaching (throughfall), root death and exudation, and translocation from one organ to another. Other than movement from roots to crown, the most common form of nutrient translocation is from foliage to stems before leaf abscission. Translocation may also occur in stemwood where nutrients in 1- to 2-year-old wood are conveyed to newer growth. There is no information available on translocation of nutrients out of branches and roots before their death, but it appears--at least in fine roots as in needles--that translocation is an effective nutrient conservation measure.

Although each nutrient has unique component pools, relative pool sizes, and transfer rates between pools, the basic concepts of nutrient transfers are similar. Figure 8 shows a simplified N cycle in a 16-year-old loblolly pine plantation. Input of N to the system is primarily atmospheric, with precipitation contributing 4.8 lb/acre (5.4 kg/ha) annually to the site. An unknown amount of N is added through dry fallout and by the direct absorption of ammonia by the foliage and the forest floor. Leaching from new and old needles by precipitation brings an additional 3.7 lb (4.1 kg) to the forest floor in throughfall, making a total input to the forest floor of 8.5 lb (9.5 kg) of dissolved N. At age 16, the forest floor contains 274 lb of N/acre (307 kg/ha) and has annual inputs from the atmosphere, leaves, branches, and fixation that total 43.5 lb (48.9 kg). Additional inputs are 43.4 lb (49 kg) from roots in both the forest floor and mineral soil. Total inputs to the forest floor and mineral soil are 86.9 lb (97.6 kg), but uptake by the trees amounts to 93.3 lb (104.6 kg). Thus, there is a net loss of N from soil and forest floor of 6.4 lb (7 kg). Approximately half of the N taken up by roots is translocated to the aboveground portions of the tree. Most of the other

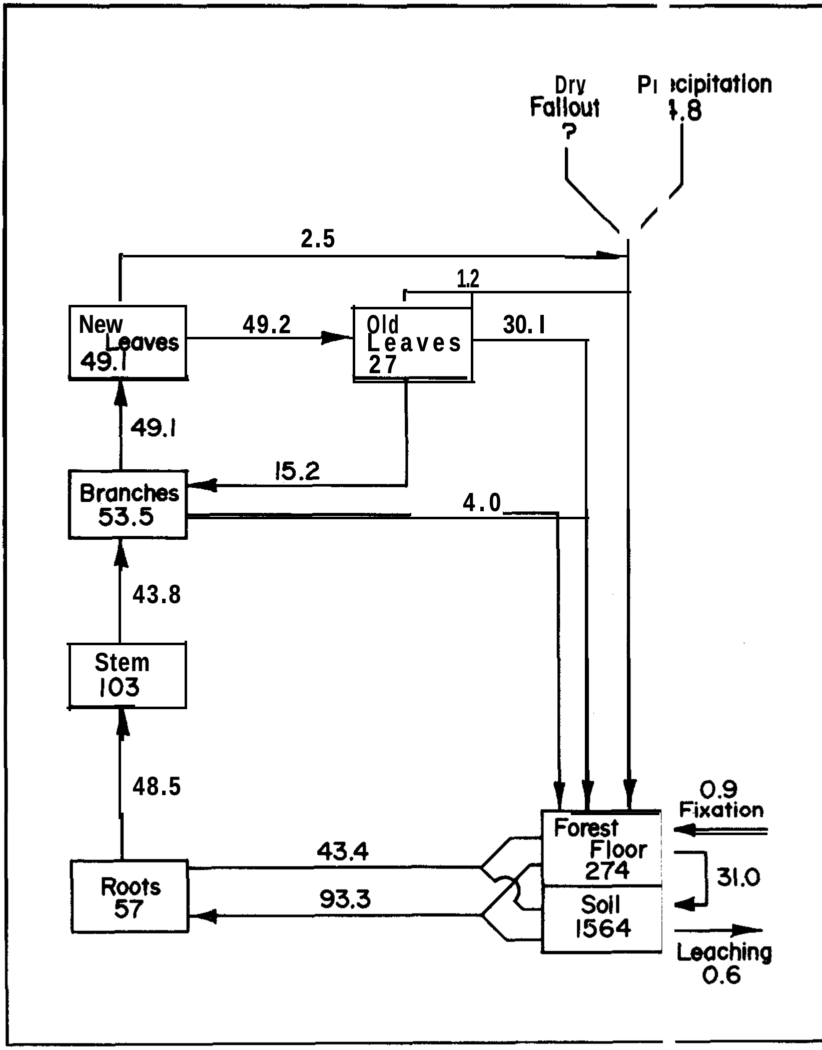

Figure 8. --The N cycle in a 16-year-old loblolly pine plantation. Values in boxes indicate N storage in individual components. Values outside boxes indicate annual N transfer. All values are in pounds per acre.

portion is recycled one or more times into short-lived nonwoody feeder roots. Little is known about these roots concentrated in the lower forest floor and upper mineral soil, except that they appear to have several cycles of biomass increase and decline during a year. Even less information is available on whether or not nutrients are translocated from the emphemeral roots to more permanent structures to be used as reserves when a new growth cycle is begun.

Of the 48.5 lb (54.4 kg) of N translocated into the aboveground portions of the tree, 4.7 lb (5.4 kg) are retained in the stem biomass, and 43.8 lb (49.1 kg) are initially moved into branches to he augmented by 15.2 lb (17 kg translocated from older needles just before their fall. Of the total branch input of 59.0 lb (66.1 kg), 4.0 (4.5) are lost through branch death, 5 9 (6.6) are retained for branch growth, and 49.1 lb (55 kg) are used for the production of new leaves. The 15.2 lb (17 kg) translocated from old needles before fall, if used for new needles, will provide about one-third of the N needs. During the next growing season, the cycle is renewed. New leaves and other components are grown, leached, aged, and lost, and the cycle begins again. As the stand ages, component sizes and their transfer rates change. Stem N will continue to gain until stand breakup, whereas foliage N will decrease slowly. As the stand ages, the annual nutrient needs decrease and the accumulated deficit in the mineral soil should be gradually restored.

Silvicultural Practices Affecting the Nutrient Cycle

The most intensive forest management in North America is practiced in the Southeast, where loblolly pine is grown in 20- to 30-year rotations. Site preparation, thinning, fertilization, and various degrees of harvesting all affect the cycling of nutrients and the ability of the site to maintain its productivity. Nutritiona relationships should be considered when manag ment alternatives such as rotation length, har est intensity, prescribed fire, site preparat on, and fertilization are selected to meet a part cular objective.

Effects of Harvesting on Nutrient Removal

Past forestry practices of long rota ions and harvesting only the bole of the tree ave led silviculturists to ignore nutrient remova and believe that nutrients take care of themsel es. New practices are forcing silviculturists to hink again. Intensive harvesting, in which mo e than the bole is removed and trees are grown i short rotations, is contemplated as a means to ubstantially increase biomass production for fi er, fuel, and chemicals. It is apparent that substantial quantities of so-called waste materi ls (branches and foliage) are available and ould be utilized. More complete utilization does more than increase the biomass supply; it also can improve site esthetics, reduce site prepa ation and planting costs, and decrease the danc er of wildfires or the need for prescribed burning. However, there are negative aspects that equire examination. Increased nutrient removals along with the increased biomass removals may c use a decline in site productivity. Residual r trients may also be lost more readily by leachinc in intensively managed stands.

There is concern that complete-tree ar-vesting combined with short. rotations car deplete the nutrient capital of a site and hence reduce future production. The quantities of nutrients removed are affected by the density of th particular stand, the age and stage of devel pment, and the biomass components that are harvested. The N losses associated with aboveground iomass harvests and stem harvest in 16- and 32-y ar-old plantations are shown in table 4. Annual nutrient removal is more affected by intensity of harvest than by rotation length. Whole-tree harvesting in both 16- and 32-year rotations results in high depletion rates, whereas stem harvest, regardless of rotation length, is approximately balanced by the N inputs from fixation and the atmosphere. In the intensive harvest system, annual nutrient drain is reduced by increasing rotation length. Nitrogen losses attributed to other management practices may be larger than those from harvest and are discussed in other sections of this report.

Most upland Piedmont soils are low in N (table 4). If all site N were completely available and productivity could be maintained as the

Table 4.--Changes in site nitrogen (N) with harvest intensity and rotation length of loblolly pine

Pool or process	Harvest age: 16 years, Whole-tree harvest	16 years, Stem harvest	32 years, Whole-tree harvest	32 years, Stem harvest
	- - - - - - Pounds/acre	- - - - - -		
Site reserves (immediately before harvest)				
Mineral soil, 0-28 inches	1,564	1,564	1,269	1,269
Forest floor	274	274	321	321
Total reserves	1,838	1,838	1,590	1,590
Harvest demand	230	103	312	208
Inputs (during rotation)				
N fixation	32	32	6	46
Atmospheric	77	77	154	154
Total input	109	109	200	200
Change due to harvest				
Per rotation	-121	+6	-112	-8
Per year (avg.)	-8	+1	6	-1

quantities of soil N declined, soil N would be exhausted after 200 to 300 years of whole-tree harvesting. However, only a small proportion of mineral soil N becomes available for plart use annually. If the percentage of total N made available is constant, then available N will gradually decrease until a balance between growth demands, inputs, and available site N is reached. Depletion and the accompanying decline in tree growth may be prevented by applying fertilizer, by adjusting rotation length, or by limiting the removal of nutrient-rich biomass in harvests.

Although the nutrient drain by lobltlly pine over a rotation appears large, the annual removal, compared with that of agricultural crops, is relatively small (table 5). Average annual production of pulpwood over a 16-year span is 3.2 tons of biomass/acre (7.2 t/ha). Averages of 5.8 lb (6.5 kg) of N, 0.8 lb (0.9 kg) of P, 4.5 lb (!.0 kg) of K, and 5.7 lb (6.4 kg) of Ca/acre (ha) ate removed annually. Harvesting the entire tree; including roots, doubles or triples annual removal but only

Table 5.--Comparison of the average annual yield and nutrient removal by a l&year-old loblolly pine plantation with that of agricultural crops

Crop	Yield	N	P	K	Ca
	Tons/acre		Pounds/acre		
Loblolly pine, whole tree	5.2	15.7	2.1	11.2	1.4
Loblolly pine, pulpwood	3.2	5.8	0.8	4.5	5.7
Corn (grain)	4.2	116	26.4	33.2	--
Soybeans (beans)	1.1	129	13.2	41.5	--
Alfalfa (forage)	3.6	189	20.7	165.8	67

about 60 percent more biomass (mostly leaves, branches, and roots of low commerical value) is produced.

Even with as severe a system as complete-tree harvest, nutrient removals are low comparel with those of annual agronomic crops. Corn, soybeans, and alfalfa can deplete the soil at 10 times the rate of loblolly pine harvest. The major reason for the difference in nutrient removal of annual and tree crops is the type of biomass harvested. In agronomic crops, harvests are primarily seeds or leafy materials high in nutrients. Soybeans, for example, contain about 5 percent N. Loblolly pine wood has an N concentration of less than 0.1 percent, and needles, a reservoir of high nutrient concentrations, contain only about 1 percent. Yields of agronomic crops are maintained by fertilizing and good management practices. If nutrients to supplement those in the soil are not supplied, crop yields fall until availability, input, and output are in balance. Soil nutrient reserves and their availability control the rate of decline in yield of unfertilized agronomic crops. On poor sandy soils, the decline can be precipitous. On fertile prairie soils, where yields are often controlled by factors other than nutrients, decades may pass before yields fall below an acceptable level. Yield decline of agronomic crops may be analogous to what can happen in loblolly pine. On poor soils, short rotations and complete harvest can, over a few rotations, lead to unacceptably low production. On deep, fertile alluvial soils, many short biomass harvest rotations may pass before there are effects of nutrient depletion on productivity. Therefore, the harvest system used on any particular site should be one that, in the long term, will minimize the loss of nutrient capital.

Influence of Harvesting on the Cycling of Residual Nutrients

In addition to the direct removal of nutrients in biomass, harvesting also influences cycling of the remaining site nutrients through chemical and physical site changes. Compared with preharvest conditions, the postharvest site has reduced evapotranspiration and the forest floor receives more solar radiation and precipitation. There is also a greater pool of nutrients from the harvest residues available for transfer to other components of the ecosystem than in the unharvested stand. Secondary effects of the harvest may include mixing organic residues with the mineral soil, transfer of nutrient-containing components from one area of the site to another, exposure of soil surfaces to erosion, and degradation of soil physical properties.

All harvesting, regardless of the intensity, will have some influence on cycling. After harvest, higher site temperature and moisture and greater availability of tree residues stimulate microbial activity. Organic residues decompose more rapidly, releasing their nutrients. The activities of nondecomposers, such as the microorganisms associated with N mineralization, are also stimulated. In one area of the North Carolina Piedmont, harvesting all trees increased N mineralization and nitrate production threefold and 36-fold, respectively, over an unharvested stand. Increased N losses due to leaching and denitrification may accompany increased nitrate production, whereas organic and ammonia N is subject to little direct loss. If the stand is thinned instead of clearcut, N mineralization will he greater than in uncut stands but still less than in clearcuts. In the thinned stand the greater portion of the mineralized N is liiely to be taken up by the residual trees, rather than lost to leaching and denitrification. N mineralization and nitrate production may be less after complete-tree harvests than after stem harvests. The reason is that complete-tree harvests remove from the site the needles and other high N-content tree parts in addition to the low nutrient woody material.

Fire

Two common types of prescribed fires used in southern forests--underburns and site-preparation burns--strongly influence nutrient cycling. Underburns are used in existing stands for fuel reduction, brush removal, range improvement, etc. These burns, which are relatively cool, remove only the most recently fallen litter and kill only the smaller hardwood stems. Site-preparation burns, which are relatively hot, are used for slash and forest floor reduction, and competition control in regeneration areas. The differences in the intensities of the burns and the amounts of materials consumed are major factors that produce the varying effects on nutrients and their cycling.

Burning can lead to nutrient losses by volatilization to the atmosphere, by increasing erosion, by ash removal from the site in air currents, and by leaching of elements that have been converted to more available or soluble form.

The most obvious effect of fire is a reduction in the forest floor. In the Southeastern Coastal Plain, 20 years of annual summer burning reduced the forest floor to 3.5 tons/acre 7.8 t/ha) compared with 13.4 tons/acre (30 t/hi) on unburned plots. Burning in the winter, after allowing a litter buildup for 4 or 5 years consumed 3.2 tons (7.3 t) or 27 percent of the 12 tons/acre (26.9 t/ha) of litter present. 'he winter burn volatilized 100 lb (112 kg) of the 300 lb/acre (336 kg/ha) of N in the litter. P'actically all of the organic N volatilized was converted to molecular N (N_2), which cannot b: used directly by plants. Burning may convert s)me organic N to ammonia, which can be adsorbe i by the soil in its gaseous state. Absorption of ımmonia on charred residues may help account for i ıcreases in soil N under some burning conditions. .ow-intensity fires used in other studies have produced similar results. As fire intensity increases, a larger proportion of the forest floor will be consumed and the amount of N volatilized will be increased. Sulfur may also be los: by volatilization, but volatilization tempera :ures of other elements are high and their loss in this manner should be small.

Although much N can be lost in burnirg, burning may influence compensating process es and also influence N availability. Biological fixation by free-living micro-organisms can ir crease after fires, but fixation by these organis ms probably amounts to only a few pounds per acre . It is severely limited by a lack of organic comp ounds to supply energy and by poor overall environrental conditions. A larger potential source of N may be fixation by higher plants. Following firt , N-fixing plants, both legumes and nonlegume:, are often prominent in the understory growth 'lush. Fixation by plants can range from a few t a hundred or more pounds per year, with the amount dependent on the plant density and the gr wth environment.

The nonvolatile components of the bu ned organic layers may either remain on the s te, filtering into the organic and mineral so 1 layers, or be moved from the site hy the rind or the convection currents set up by the fir :. In one prescribed fire in South Carolina (Kolama and Van Lear 1980), nutrients lost from the 1 tter (L) layer (nearly 60 percent) were approximately proportional to the fraction of the L layer consumed by fire (table 6). Only small nutrient increases were measured in the F and H organic layer;, and it was concluded that most of the nutrient; had been lost from the site as ash in air currents and smoke created by burning.

Recurrent burning over long periods can transfer nutrients from the forest floor to the mineral soil. A severe treatment, annual burning for 20 years in the summer, reduced nutrient contents of the forest floor by 12, 18, 89, and 19 lb/acre (13, 20, 100, and 21 kg/ha) for P, K, Ca, and Mg, respectively. Roughly corresponding increases in Ca and Mg were found in the mineral soil, but no increases in P or K were recorded.

Table 6.--Quantities of nutrients in forest floor layers of four loblolly pine plantations before burning, and percentage change immediately after prescribed fire

Nutrient and condition	L layer lb/acre	L layer % change	F + H layer lb/acre	F + H layer % change
Calcium				
Preburn	33.9	--	80.3	--
Postburn	15.2	-55	88.4	+10
Magnesium				
Preburn	13.4	--	23.2	--
Postburn	4.5	-66	24.0	+3
Potassium				
Prehurn	16.1	--	37.5	--
Posthurn	6.3	-61	36.6	-2
Nitrogen				
Preburn	50.8	--	262.5	--
Postburn	27.7	-45	245.5	-6
Phosphorus				
Preburn	6.3	--	17.0	--
Postburn	2.7	-57	18.7	+10

Source : Adapted from Kodama and Van Lear 1980

These quantities, both lost and transferre to the mineral soil, had a very small effect on t tal site nutrients, especially on an annual ba is. Thus, burning to rapidly release nutrients will not alleviate site nutrient deficiencies c used by infertile soils. Good prescribed burning 'or hazard reduction and vegetation control wi 1 have little influence on nutrient loss or trans 'er.

In addition to fire intensity and amo int of organic material consumed, soil properties often determine the fate and effects of released nutrients. Released nutrients may greatly affe:t pH and nutrient availability in soils with low ex:hange capacity such as sands, but their influenc: will be limited in soils with high exchange cap:city, such as clays. Similarly, due to these pr)perties and the differential potential for leaching losses, plant response to burning may be c-amatic and short-lived on sand but moderate and e:xtended on clay.

Properly applied hazard-reduction burls that remove only a portion of the L layer and r one of the F and H, and do not expose mineral soil, do not increase runoff. Nutrient loss via rt noff or erosion, therefore, is not appreciably increased. Soil erosion can be the most obvious conse quence of burning. However, in only one of six turning studies by Ralston and Hatchell (1971) (ore in the North Carolina Piedmont) did erosion grea ly exceed a soil loss of 1 inch (3 cm) in 1,00 years or an annual loss of 0.3 tons/acre (0.67 /ha). This rate is the soil-loss rate estimated to take place as a normal geologic erosion proces .

Burning may indirectly affect nutrie t cycling by altering the micro and macro flo 'a and fauna of the forest floor. In long-term re-scribed burning programs, the populations of spore-forming microfungi or bacteria are not reduced sufficiently to impair soil proce:ses. Intensive fires, however, may reduce popu ations dramatically, temporarily sterilizing the soil. This is most likely to occur in fires where slash has been piled and burned for disposal.

Nitrogen fixation by free-living soil micro-organisms has been found to increase after burning. The amounts fixed range from about 1 lb/acre/year to as high as 12.5 lb/year in some areas. Comparable unhurned areas fix less than 0.05 lb annually. Fixation rates by free-living organisms are limited by a lack of an energy source and available P in most forest soil;.

Individual low-intensity prescribed fires do not cause important losses of nonvolatile nutri-ents. However, the long-term cumulative losses of the volatile nutrients, especially N, can be sub-stantial--over 100 pounds per acre during a rota-tion. Nevertheless, this quantity is small in relation to that removed in a complete hardest of aboveground biomass plus the losses that accompany intensive site preparation. In intense burns, as in uncontrolled wildfires and those used for slash reduction, important decreases of site N and sul-fur through volatilization can occur. Losses of nonvolatile elements caused by intense fires are usually associated with ash carried from tie site rather than by postfire leaching. Losses of these nonvolatile elements can be large, but even they are smaller than can occur in harvest and site-preparation activities.

Site Preparation

Site preparation controls competition, re-moves impediments to planting, and modifies the site nutritionally and physically for improved tree growth. If properly handled, competition control and the removal of planting impedinents will not adversely affect the nutrient cycle. However, movement of organic matter and soil to produce an immediate gain in seedling growth and survival may have negative effects on nutrient availahility later in the rotation.

One of the most intensive systems for site preparation is shearing, rootraking, and windrowing followed by disking for final competition control. This system tends to concentrate surface soil, roots, forest floor, and logging debris in windrows and to mix any organic residues between the windrows with the mineral soil. On infertile soils, such nutrient displacement can seriously affect the growth of the present rotations as well as of successive ones. The result is superior growth of trees adjacent to windrows compared with those farther from the windrows. In a flatwood site in Florida, Morris and others (1983) found that although windrows occupied only 6 percent of the site, these areas contained from 10 to 40 percent of the total or extractable nutrient reserves in the system. These nutrient displacements were larger than were the removals associated with harvesting the stand. N displacement into windrows was six times the 5.3 lb N/acre (5.9 kg/ha) removed in the bolewood harvest. Displacements of P, K, Ca, and Mg into the windrows also equaled or exceeded those in the harvest removal.

Erosion following soil disturbance transports nutrients in both dissolved and solid forms. Losses from erosion may be greater than those estimated from average nutrient concentrations in sediments due to the selective transportation of organic and mineral-organic particles. Only on sloping sites and those without protective cover, however, should overall nutrient reserves be significantly affected by erosion. Local areas affected by improperly constructed or located roads and skid trails may be severely impacted. Leaching losses of all elements except N are usually small.

Site preparation can significantly affect biological activity and associated nutrient availability. Removing the protective plant canopy and forest floor by shearing, piling, and disking can raise soil temperatures 3.6 to 9 °F (2 to 5 °C) above those that occur with low-intensity treatments such as chopping. Fewer plants on prepared sites also reduce transpirational losses and result in higher soil moisture. The warmer and wetter conditions coupled with the mixing of forest floor and soil promote greater biological activity. Increased activity is especially important in the conversion of organic N to nitrate N, which is subject to leaching and denitrification. In late summer, the nitrate pool in the surface soil of a sheared, piled, and disked area on the Piedmont of North Carolina was 10 lb/acre (11 kg/ha) compared with less than 1 lb for a chopped-only treatment. Differences of similar magnitude were also found in soil solutions at the 28-inch (70 cm) depth. Use of herbicides and the elimination of vegetation greatly increased nitrite in both surface soil and at the 28-inch depth, adding to the loss of site N.

Nutrient losses from site preparation, especially those of N, may be reduced by mainlaining an intact forest floor and by allowing tht planted site to revegetate normally, controlling only the most troublesome competing vegetation. These soil covers will moderate the soil temperature and moisture increases associated with intensive site preparation that promote high biological activity. The forest floor and organic residues can also immobilize mineralized N, and the small plants use any excess mineralized N. Nitrogen retained in these pools may be utilized for tree growlh later in the rotation.

The mineralization rate of organic N, as influenced by site-preparation intensity, has important implications for tree growth. Models relating N release to the intensity of sile preparation and N growth requirements are shown in figure 9. After both high and low intensities of site preparation, there is an initial excess of mineralized N--more than the amount taken up by the small root systems of the young trees. Under

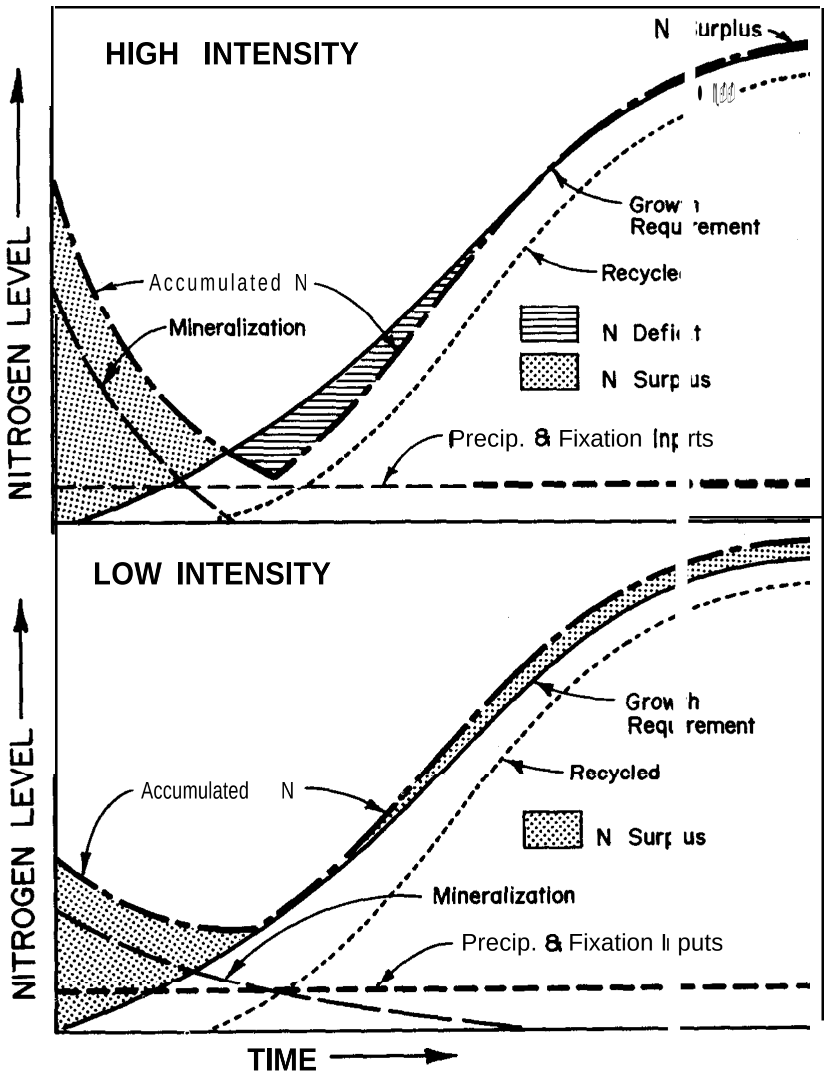

Figure 9.--Theoretical effect of site-preparation intensity on long-term N reserves. High-intensity site preparation (above) includes competition control and mixing of the forest floor and mineral soil. Low-intensity treatment (below) includes only competition control. (Adapted from Burger and Kluender 1982.)

high-intensity preparation, the N surplus is larger and is lost more rapidly than under low-intensity preparation. Late in the rotation, this loss of N reserves causes poor tree growth. Even later, N reserves may be lacking for growlh in subsequent rotations. Thus, intensive preparation that changes the rate and cycling pathway! of nutrients may provide for rapid early growth but can result in reduced growth over the long term.

Fertilization

Forest fertilization has become a standard practice for many forest products companies that demand high productivity from loblolly pire sites. Fertilization can modify nutrient cycling through changes in the size of components of the cycle (the pools), and in the transfer rates between pools. For example, fertilization with a soluble nutrient source may influence not only the leaching rate of the applied element but also those of other elements competing for exchange sites in the soil. Additions of nutrient: in short supply may also increase the uptake of other nutrients as tree growth accelerates. These two simple examples, among many, can substantially change nutrient cycling on a site, especially if fertilization is accompanied hy modifications in site preparation, rotation length, harvesting procedures, and other forest management practices.

In addition to alleviating naturally occurring nutrient deficiencies, a second role for fertilizer is to replace nutrients removed via harvest or as a consequence of site disturbance. Unfortunately, using fertilizers to replace nutrients is more complex than simply substituting for those removed in a one-to-one ratio. Information on nutrient uptake by loblolly pine over long periods is limited, but what exists shows overall efficiency of fertilizer use is low. For applied N, about one-quarter is taken up by trees, one-quarter is held on the site in other components, and the remainder is lost by leaching and volatilization. Thus, for N, if inputs are needed to balance losses, between 2 and 4 pounds of fertilizer N would have to be applied for every pound removed in management activities.

Phosphorus utilization during the first rotation is similar to that of N. However, unlike N, little P is lost from the site. Little is known about the applied P availahility during succeeding rotations. No information is available on the uptake-application ratios of other nutrients in loblolly pine stands.

The point at which nutrient replenishment is required for yield maintenance is not known. When replenishment of most nutrients is attempted, small quantities of nutrients applied several times during a rotation may be better than one large application at the time trees are established. Perhaps even greater knowledge and effort will be required for efficient nutrient maintenance than for fertilization to alleviatt obvious nutrient deficiencies.

Soil-Improving Plants

Wild legumes and other N-fixing plant! help maintain the ecosystem's supply of N, and as understory contribute to the cycling of other nutrients from the lower into the upper soil layers and the forest floor. At certain times during the loblolly pine rotation, it may be appropriate to establish soil-improving plants. Ideally, these plants should not have severe competitive or allelopathic effects on the pines, should fix and release important quantities of N, and should be tolerant of the severe site conditions that are often found in loblolly plantations.

In one young loblolly plantation on the North Carolina Coastal Plain, trees were fertilized with

P and grown in stands of lespedeza (Lespe eza cuneata (Dumont.) G. Don and L. thunbergi -(DC Naki) established to provide biologically fixed N. Trees with the P plus lespedeza, at age 7 had a volume of 10 cords/acre (89.6 m^3/ha) comp red with 8.4 cords (75.2 m^3) for trees with P fert lizer alone. During the initial years of lespe eza development, foliage of trees in the lesp deza stands contained higher concentrations of N than did controls or trees receiving only P. s lespedeza biomass declined with stand closure, foliar N concentrations, regardless of treatment, ecame similar. The lespedeza was estimated to ave added 400 lb of N/acre to the site over i s 4-year period of maximum growth.

There may be instances when the seco dary effect of legumes may be as important as hat of the N fixed. Deep-rooted legumes may red rce leaching losses by taking up nutrients fr m below the rooting zones of young trees. Legumi ous litter, high in N, may speed up forest floor decomposition, hastening nutrient release and cycling. Legumes may also be capable of improving he physical properties of soil, thereby increasi g the potential soil volume from which trees ma extract moisture and nutrients.

Intensive Forest Management and Productivity

Barring severe erosion or soil and utrient displacement, it is unlikely that even th most intensive harvesting and silvicultural procedures will transform productive loblolly pine cites into unproductive ones in a rotation or two. Existing management systems, however, are based upon sustained yield with the implication that productivity will be maintained. Yet, there is a dearth of long-term data showing whether presenl management is meeting sustained-yield objectives.

Despite many limitations and unknowns, nutrient budgets may provide a method for com- paring effects of alternative forestry practices on ecosystem nutrients (table 7). Although only a budget for N is presented here, budgets can be prepared for other nutrients and the implications similarly studied. Some nutrient losses during harvest and regeneration are unavoidable, but the quantities removed depend largely on the manage- ment techniques adopted and the skill with which they are carried out. For example, employing three short rotations rather than a single 60-year rotation increases stem yield from 87 to 144 tons/ acre (195 to 323 t/ha) with only proportionate increases in nutrient removal (Switzer and others 1978). If, however, the entire aboveground por- tion of the loblolly stand is harvested, N removal increases from 155 to 634 lb/acre (174 to 11 kg/ha) and P from 12 to 59 lb/acre (13 to 6 kg/ha) or more than fourfold during the 60 year

Table 7.--Effects of stem and whole-tree harvest of loblolly pine and site-preparation practices on nitrogen demands at rotations of 16 and 32 years, in pounds per acre

Practice or process	16 years Whole tree[a]	Stem	32 years Whole tree[a]	Stem
	DEMANDS OF N			
Harvest	230	103	382	208
KG, windrow, disk	209	336	209	336
Erosion				
Kg, w, disk (Piedmont)	28	28	28	28
Chop (Piedmont)	5	5	5	5
Prescribed burn	60	60	120	120
Slash burn	0	120	0	136
Leaching				
Disk or bed	32	32	40	40
Chop or herbicide	16	16	20	20
	INPUT OF N			
Atmospheric deposition	77	77	154	154
Nitrogen fixation				
No seeding	32	32	46	46
Seeded legumes	400	400	400	400

[a]Excluding roots.

period. When nutrient changes of this ma! nitude can occur as a result of a management dec sion, the long-term ability of the ecosystem to support this yield must be examined. If the conc usion is negative, there are three basic remedies: (1) apply fertilizers, (2) change the rotatio length, and (3) harvest less biomass. If one or I ore of these remedies are not adopted, yield red ctions in future rotations must be anticipated.

Other causes of nutrient outflow fror a site may be as great or greater than that of tle harvest. Intensive site-preparation practic s such as rootraking and windrowing are one such cause; prescribed burning is a second. Surprisi gly, erosion, although conspicuous, seldom cau es major nutrient losses, and these losses can be inimized by converting from intensive to conservat ve site preparation. Similarly, losses from leacl ing can be reduced by using conservative site-pre aration treatments.

Ry examining various forest managemelt systems and their associated nutrient remova's, some idea can be ohtained of their overall imp ct on the ecosystem and its ability to provide utrients for sustained yield. Several systems witl widely differing N removal rates are shown in talle 8. Included are both intensive and conservat ve management systems. Even the most conservat ve system listed, the 16-year stem-only harvest followed by chopping, causes a small net loss of N without legumes. With a 32-year rotation and cho ping, annual loss would be similar, 1 lb/acre. These data indicate that when stem harvest is tle largest contributor to N removal, rotatio age does not influence nutrient loss on an an ual basis. Nutrient losses associated with tle stem are uniform because stem biomass of the s and increases fairly uniformly to maturity. f the entire tree is harvested, nutrient losses of the stand allocated over the lengthened rotat on are reduced due to stand foliage and branch b omass peaking at an early age.

Table 8.--Changes in system nitrogen with various combinations of rotation length, biomass removal, and site preparation in loblolly pine plantations

Rotation length (years)	Biomass removal	Site treatment	Rotation	Annual
			Pounds/acre	
16	Whole tree	1	-450	-29
16	Whole tree	2	-82	-5
32	Whole tree	1	-579	-18
32	Whole tree	2	-225	-7
16	Stem	3	-15	-1
16	Stem	4	+233	+15
32	Whole tree	5	+27	+1
32	Stem	6	-148	-5

Treatments:
1. KG-windrow, disk, prescribed burn (PB).
2. Treatment 1 plus legumes.
3. Chop.
4. Chop, slash burn, legumes.
5. Chop, PB, legumes.
6. Herbicide, PR, natural regeneration.

Site-preparation practices rank first or second as causes of nutrient drain. Rootr king and disking are sometimes combined with be lding to impose severe nutrient demands on the s te. Although good survival and early growth ca I be obtained with these methods, less nutrient costly alternatives may give equally good yields ver the long term. Chopping and herbicide applica ions may substitute for intensive procedures, e spe- cially if site-to-site adjustments in plan ing and preparation can be made.

Fertilization can offset nutrient los es, but for N its effect is short term and the pro ortion of the applied N recovered by trees is oft n low.

Legumes may be an alternative source of N However, their utilization is more complex than the application of fertilizer. Seedbed preparation, fertilization, selection of species, and competition are considerations if biologically fixed N is to supplement or supplant N fertilization.

Quantities of nutrients added as fertilizer to compensate for those removed from the site by harvest or lost during regeneration are not of equal value in maintaining site productivity. For example, the N lost in erosion, windrowing, burning, and harvesting is derived mostly from organic compounds that are normally mineralized and made available to higher plants over many years. Organic matter and organic N are essential to maintain the physical, chemical, and biological properties of the soil; therefore, fertilization may be a poor and economically unsound substitute for N losses, especially on infertile sites already low in organic matter.

Based upon the known deficiencies and probability of losses from the loblolly pine ecosystem, the impacts of intensive management practices on site nutrients are in the order of N > P > K > Ca > other elements. Like N demands, those for P and K under intensive forest management exceed natural inputs. Phosphorus deficiency is less difficult to correct than N because P persists in the soil and trees are able to utilize it in slowly soluble forms. Rock phosphate is a cost-effective, slowly soluble source of P and, when available, may be substituted for triple superphosphate and other soluble forms. When large amounts of biomass are removed and intensive site preparation causes accelerated leaching, K and Ca deficiencies will eventually limit growth on many soils. Potassium can persist because it can be taken up in luxury quantities and cycled by the vegetation with few leaching losses. Calcium, however,, is cycled more slowly and when accompanied by N fertilization or high mineralization of native N is readily leached with the nit-ate ion. Its loss could reduce the productivit/ of base-deficient sandy soils.

As a solution to the problem of excess nutrient removal over that of input, it has beer suggested that an "ecological rotation" be matched to site. In this system, rotation length and harvest are related to nutrient ·input from the atmo sphere and from soil mineral weathering. While ecologically sound, this approach ignores the general lack of primary nutrient-containing minerals in soils of the South and the low and variable atmospheric input rates of the different nutrierts. Furthermore, most rotation lengths would hive to be increased to such an extent that annual production would fall. Forest managers would also lose flexibility of forest production. The best system for minimizing the potential for a long-te m decline in yield is a forest manager with knowledge of and the ability and freedom to app y good nutrient cycling principles.

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Foresters' primer in nutrient cycling. A loblolly pine management guide, Gen. Tech. Rep. SE-37. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1986. 42 pp.

The nutrient cycle, which includes the input of nutrients to the site, their losses, and their movement from one soil or vegetation component to another, can be modified by site preparation, rotation length, harvest system, fertilization, and fire, and by using soil-improving plants. Included is a report on how alternative procedures affect site nutrients, and provides general principles that can be followed to enhance long-term productivity of loblolly pine.

Keywords: *Pinus taeda*, nitrogen, phosphorus, potassium, rotation length, nitrogen fixing, whole-tree harvesting.

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